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Carbon stock estimation and changes associated with thermokarst activity, forest disturbance, and land use changes in Eastern Siberia

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Highlights

- Thermokarst formation accumulates organic matter and flooding increases C stocks.
- Forest disturbance significantly changed the C balance.
- Arable land abandonment restores SOC and TSC stock, but its rate gradually decreases.
- Redistribution of the C stock has been occurred under the climate change and human activities.
- Root biomass plays an important role in SOC accumulation and vertical distribution.

ABSTRACT

This study was conducted to evaluate the change in total soil carbon [TSC = litter carbon (LIC) + soil organic carbon (SOC) + soil carbonate carbon (SCC)] associated with recent thermokarst activity and forest disturbance induced by the climate change and land use change in the permafrost-affected soils of Eastern Siberia. TSC stock from 80 sites in three types of the ecosystem: forests, arable land, and thermokarst were analyzed. The SOC content was positively correlated with root C density in all ecosystems. In the forest and arable land ecosystems, soil texture strongly affected SOC content, but water content was the main factor in SOC accumulation in the thermokarst ecosystem. Although the composition ratio of TSC stock significantly differed among the ecosystem, SOC was the main component of the TSC in all ecosystems. SOC and TSC stocks in thermokarst ecosystem (137.1 ± 125.5 Mg SOC ha^{-1} 30 cm^{-1} and 150.5 ± 123.9 Mg TSC ha^{-1} 30 cm^{-1}) were significantly higher than those in the forest (28.3 ± 13.5 Mg SOC ha^{-1} 30 cm^{-1} and 51.4 ± 20.9 Mg TSC ha^{-1} 30 cm^{-1}) and arable land ecosystem (41.9 ± 16.9 Mg SOC ha^{-1} 30 cm^{-1} and 54.6 ± 23.1 Mg TSC ha^{-1} 30 cm^{-1}), suggesting that thermokarst formation accumulates C. In the thermokarst ecosystem, significantly higher SOC stock was observed in moderately-wet and wet grassland than dry grassland suggesting that flooding increases C by suppressing organic matter decomposition. Among the forest ecosystem, forest disturbance significantly altered the C balance. Forest fire did not change the

SOC and SCC stock but significantly burned the LIC stock at an average rate of 51.7 ± 65.0% of the LIC. Water damage to the forest significantly increased the SOC stock by increasing the water content, but 58.5 ± 62.4% of the LIC stock was dismissed. Forest cultivation significantly reduced TSC stock at an average rate of 37.3 ± 47.2% by mineralization of the LIC. On the other hands, abandonment of arable land significantly restored TSC stock at an average rate of 92.4 ± 83.5% by increasing C input. This study revealed that redistribution of the C stock has been occurred under the climate change and human activity.

Key words: climate change, Cryosol, permafrost-affected soils, soil carbon stock change.

1. Introduction

In the northern circumpolar region, an area of about 17.8 million km^2 is occupied by permafrost-affected soils (Hugelius et al., 2014). Permafrost regions occupy approximately 25% of the terrestrial surface of the Northern Hemisphere, and more than 60% of the permafrost is found in Russia (Brown and Grave, 1981). It is estimated that nearly one-third of the world's soil organic carbon (SOC) stock present in the top 3 m of the soil profile (approximately 1035 Pg C) is stored in arctic and boreal regions (Hugelius et al., 2014).

The central Yakutia region is a well-known example of a thermokarst region (French, 1996). Desyatkin et al., (2013) and Crate et al., (2017) summarized the specific feature, Genesis, and dynamics of the thermokarst. Around 16,000 thermokarsts are located in the Central Yakutia lowland with a total area of 440,000 ha, which represents 17% of the total land area of Central Yakutia (Bosikov, 1991). C stocks in thermokarst soils considerably increase compared with intact forest (Desyatkin and Desyatkin, 2006; Matsuura et al., 1994). However, the exact rate of C stock in thermokarst ecosystem have not been studied well.

Global warming is expected to be most pronounced at high northern latitudes (IPCC, 2014). Between 1961 and 2010, the mean annual air temperature at Yakutsk, Russia increased by 2.5 ºC (Fedorov et al., 2014), and heavy precipitation events exceeding 20 mm d^{-1} significantly increased during 1936–1994 (Easterling et al., 2000) and the climate has been unusually wet

since 2005 (Iijima et al., 2014; Ohta et al., 2014). As a result, a significant increase in thermokarst activity has been observed since the early 1990s. The melting of the tops of ice wedges is causing subsidence, the deepening and expansion of thermokarst depressions, and the growth of thaw ponds that form larger lakes (Crate et al., 2017).

Forest disturbance affects the C budgets of Siberian forests (Kukavskaya et al., 2016). Recently, severe forest disturbances have been reported on the Siberia as a result of forest fires (Conard et al., 2002; Isaev et al., 2002). Forest fires may be becoming more frequent as a result of regional climate change (Kukavskaya et al., 2016). The effects of fire on C stocks are highly variable and mainly depend on the intensity of the fire (Cui et al., 2014). The increased precipitation resulted in warming and wetting of the active layer and near-surface permafrost, which persisted in subsequent years (Iijima et al., 2010, 2014), and the larch forests in the central Lena River basin were gradually damaged. Flooding may change C budgets in forest ecosystems, but the effects of water damage on C stocks have not been extensively studied in boreal forests (Ohta et al., 2014).

Central Yakutia is one of the most northern agricultural centers in the world. During the second half of the 20th century, the Soviet government began the gradual establishment of the state farm system (Takakura, 2015). In the early 1990s, after the collapse of the Soviet Union, the area of farmland drastically decreased in Russia (Ioffe and Nefedova, 2004). According to

Lyuri et al. (2010), about 45.5 million ha of arable land were abandoned between 1990 and 2007, which was the most widespread and abrupt land use change in the 20th century in the northern hemisphere (Lyuri et al., 2010). Land use changes significantly affect the amount of C stored in the soil (Gelaw et al., 2014). The IPCC (2013) estimate that land use changes account for 33% of anthropogenic global C emissions (180 Gt C was emitted from 1750 to 2011). Converting natural forests into agricultural land results in the mineralization of organic matter (OM), which leads to a decrease in SOC stocks (Don et al., 2011). In contrast, the abandonment of arable land and the recovery of natural vegetation result in SOC accumulation (Kalinina et al., 2015; Kurganova et al., 2015).

From this background, boreal region and permafrost-affected soils have been considered as a hot spot of the soil C stock change. This study had the following aims: firstly, to evaluate C stocks in the main land use types of Central Yakutsk where the C stock estimation has been poorly conducted: secondly, to estimate changes in C stocks associated with recent thermokarst activity, forest disturbance, and land use changes caused by human activity: thirdly, to ascertain what main factors affect C stocks.

2. Material and methods

2.1 Study site

The study was conducted in Central Yakutia, Eastern Siberia, Russia (Fig. 1). The climate of this region is extra-continental. Average annual temperature has been -9.7°C, with annual precipitation of 235 mm. Recorded minimum and maximum temperatures are -63°C in January and 38.3°C in July, respectively. The maximum monthly average precipitation is 39 mm in both July and August. The minimum monthly precipitation is 6 mm in March. The soil parent material in this region is composed mainly of Upper Pleistocene to Holocene alluvial deposits with continuous permafrost (Fig. 1).

2.2. Typical ecosystems and land use types in the study region and soil classification

There are three ecosystems in this region: forest, arable land, and thermokarst. The forest ecosystem can be subdivided into larch forest (LF), burned forest (BF), water-damaged forest (WF), and pine forest (PF). In the LF, the forest consists of larch *(Larix gmelinii)* trees. In the BF, following the fire event, the dominant vegetation consisted of several species of grass, and fireweed (*Chamenearіom angustifolium*). Thermokarst lake expansion and a flood from a stream damaged the surrounding forest (Iijima et al., 2014; Ohta et al., 2014). During this period, the vegetation composition changed from dense cowberry (*Vaccinium vitis-idaea*) to grasses

and shrubs with a high-water tolerance (Ohta et al., 2014). In the WF, the dominant species has shifted from larch to white birch (*Betula platyphylla*). PF (*Pinus silvestris*) only grows in sandy soil, and the soil's high permeability and the acidic pine litter result in podzolization.

Soils which having a cryic horizon starting ≤ 100 cm or a cryic horizon starting ≤ 200 cm from the soil surface and evidence of cryoturbation in some layer within ≤ 100 cm of soil surface are classified as Cryosols (IUSS Working Group WRB, 2015). Soil types and land use types were well correlated in this study region.

The active-layer thickness in the LF and BF is less than 2 m, and the soil is classified as Cryosols (IUSS Working Group WRB, 2015). However, the active-layer thickness in the WF and PF is deeper than 2 m, and the soils are mainly classified as Fluvisols and Spodosols, respectively (IUSS Working Group WRB, 2015).

The arable land ecosystem can be subdivided into working arable land (WAL), abandoned arable land (AAL), and abandoned arable land invaded by new trees (NAL). Oats (*Avéna satíva*) are cultivated on the WAL. On the AAL, during self-recovery, the vegetation developed towards a steppe ecosystem, with *Stipa capillata*, *Chenopodium album*, and *Lappula squarrosa* being dominant. On the NAL, larch dominates, and grows to 3–4 m in height. The active-layer thickness is deeper than 2 m, and the soil is mainly classified as Cambisols (IUSS Working Group WRB, 2015).

Thermokarst formation process has four stages: byllar, dyede, tuumpu and alas (Fig. 2). Ice melting initiates small surface subsidence with the formation of rounded mounds of up to 1 m in height and several meters in diameter (the byllar stage). Progressive melting of the ground ice results in the development of small lakes and the death of tree vegetation around their banks (the dyede stage). Then, when the major part of ground ice is molten, typical thermokarst lake of rounded shape appear (the tuumpu stage). Under arid conditions, these lakes are partly dried, and meadow vegetation appears on their banks (the alas stage).

The thermokarst ecosystem can be subdivided into dry grassland (DG), moderately wet grassland (MG), wet grassland (WG), and pingo (PG) based on soil type, waterlogged status, vegetation, and topography. DG is found on the elevated periphery of depressions, and the dominant species are *Puccine11ia tenuif1ora*, *Hordeum brevisubulatum*, and *Carex duriuscula*. MG and WG are characterized by lacustrine deposits (LD) horizons. The high soil moisture content of the MG promotes a high productivity of grassland vegetation, and *P. tenuif1ora*, *Po1ygonum aviculare*, and *C. duriuscu1a* dominate. WG is found on the lowest part of the depressions around the lakes. The dominant species are *Carex wiluica meinsh*, *A1opecurus aruninaceus*, *Schoenoplectus lacustris*, and *Phragmites communis.* PG is round mounds, which form when water in the ponds refreezes (Desyatkin et al., 2013). The dominant species are *Artemisia jacutica*, *Artemisia dracunculus*, and *Erysimum cheiranthoides*. The active-layer

thickness is deeper than 2 m, and DG, MG, WG, and PG soils are mainly classified as Stagnosols, Fluvisols, Histosols, and Cambisols, respectively (IUSS Working Group WRB, 2015).

2.3. Soil sampling

Soil profile surveying and sampling were conducted in 2014 and 2015 in four areas on the left bank and ten areas on the right bank of the Lena River (Fig. 1). In total, 71 soil survey sites were included: 15 of LF, 3 of BF, 3 of WF, 4 of PF, 5 of WAL, 14 of AAL, 7 of NAL, 8 of DG, 3 of MG, 5 of WG, and 4 of PG. Sampling sites were selected that represented the main vegetation types and geomorphology of the land use. We could not find enough sites for some land uses because of the limitation of the area. Therefore, we decided to secure at least three sites for each land use to compare statistically.

The forest was cultivated during two main periods. In the Nemmere area, cultivation started in 1965 and was abandoned in 1978 or 1994. In the Unakh and Tunguly areas, cultivation started in 1985 and was abandoned in 1994 and 2009, respectively.

Using a 100-mL steel cylinder, two replicates of both composite and undisturbed samples were taken from each horizon at a depth of 50 cm, and one replicate was taken at a depth of 100 cm. Soil sampling was conducted at the apex of the triangle with 10 to 30 m each side to

evaluate the variation of C distribution.

Soil profiling survey data obtained by Desyatkin et al. (2013) in 2013 from nine other sites (six AAL, one DG, one MG, and one WG) were also used. At the LF, BF, WF, PF, and NAL sites, three replicates from the organic horizon were sampled using a 100-mL steel cylinder.

2.4. Sample preparation and analysis

2.4.1. Sample preparation

To measure the physico-chemical properties of the mineral soil and litter, composite samples were air-dried and passed through a 2-mm mesh sieve that removed stones, roots, and other plant residues. The samples for the C content analysis were ground and further sieved through a 0.5-mm mesh sieve to minimize the variation of the measurement.

2.4.2. Organic carbon and carbonate carbon content of soils and the organic horizon

Wet oxidation using $K_2Cr_2O_7$ was conducted to determine the SOC content of the mineral soils. Soil carbonate carbon (SCC) content was calculated from the quantity of CO_2 produced by adding 10 mL 10% HCl (Wt/Wt) to 0.5–1.0 g dry soil sample. The volume of CO_2 produced was measured using an aqueous manometer. The weight of CO_2 was calculated from its volume at standard temperature and pressure and was used to calculate the level of carbonate.

The loss on ignition (LOI) method (weight, %) at 550°C (for 6 h) was used to determine the OM content of the organic horizon. The LOI method has the potential to overestimate OC content compared with the dry combustion method (Campos, 2010). Therefore, we modified the values obtained using the LOI method using a factor of 2, based on the assumption that organic matter is 50% carbon (Pribly, 2010).

2.4.3. Soil physico-chemical properties

The 100-mL core samples were oven-dried at 105 °C for 48 h to measure the water content and bulk density (BD). Soil texture was determined by the pipette method. Soil pH and electrical conductivity (EC) in 1:5 soil:water suspensions were measured using a pH meter (F-8 pH meter, Horiba, Japan) and an EC meter (B-173 conductivity meter, Horiba, Japan), respectively. Exchangeable potassium (K^+), sodium (Na^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) were extracted with 1 M ammonium acetate (pH 7). K^+ and Na^+ concentrations were measured using flame photometry, and Ca^{2+} and Mg^{2+} concentrations were measured using atomic absorption spectrophotometry.

2.5. Root sampling and analysis

Root sampling was conducted in 2014 at 31 sites (four of LF, three of WAL, six AAL, three

NAL, five of DG, three of MG, three of WG, and four of PG). Root samples were collected every 10 cm at a depth of 50 cm. Rectangular blocks of soil (25 × 25 × 10 cm) were washed with water through a 1-mm mesh sieve to separate the soil materials. Root samples were air-dried and crushed using a mill to pass through a 0.5-mm mesh sieve. The root samples (three replicates) were analyzed using the dry combustion method (Flash 2000 NC-Soil, Thermo Fisher Scientific).

2.6. Data calculation

2.6.1. C stock

The total SOC stock profile at each site was calculated as the sum of the component soil horizon SOC stocks at a depth of 0–30 cm.

The SOC stock (Mg C ha^{-1}) of each horizon was calculated as follows:

$$\text{SOC stock} = BD \times SOC \times D \times 10 \quad \text{(Eq. 1)}$$

where BD is soil bulk density (Mg m^{-3}), SOC is soil organic carbon content (mg C kg^{-1}), and D is soil sampling depth; 10 is a factor to adjust the units. The SCC and C in the organic horizon (litter carbon, LIC) stocks were calculated using the same method. The total soil carbon (TSC) stock was calculated as the sum of the LIC, SOC and SCC stocks. In this study, any coarse fragments did not appear in the soil profile.

2.6.2. C recovery rate after arable land abandonment

The annual average C stock recovery rate (C_{rec}, Mg C ha^{-1} 30 cm^{-1} yr^{-1}) after arable land abandonment was calculated using the equation suggested by Kurganova et al. (2014):

$$C_{rec} = (C_{AAL\ (or\ NAL)} - C_{WAL}) / T \qquad \text{(Eq. 2)}$$

where $C_{AAL\ (or\ NAL)}$ and C_{WAL} are the C stocks at a depth of 0–30 cm at each AAL (or NAL) site and the mean at all WAL sites, respectively. T is the number of years after abandonment. C_{rec} was calculated based on the sites in Nemmere, Tunguly, and Unakh in which the number of years after cultivation was abandoned is known.

2.7. Statistical analysis

Statistical analyses were performed using R version 3.3.3 (R Development Core Team, 2016). Differences in SOC, SCC, LIC, and TSC stocks among the ecosystems, land use types, and soil types were determined by conducting one-way ANOVAs and Tukey-Kramer tests.

3. Results

3.1. LIC, SOC, SCC, and TSC stocks

LIC, SOC, SCC, and TSC stocks in the organic horizon and 0–30 cm soil layers are shown in Fig. 3.

LIC stock in the forest ecosystem (16.1 ± 10.0 Mg C ha^{-1} organic $horizon^{-1}$) was significantly higher than in the arable land (0.4 ± 1.4 Mg C ha^{-1} organic $horizon^{-1}$) or thermokarst (0 Mg C ha^{-1} organic $horizon^{-1}$) ecosystems. Among the forest ecosystem, LIC was significantly higher in LF than in the other land uses.

The SOC stock was significantly higher in the thermokarst ecosystem (137.1 ± 125.5 Mg C ha^{-1} 30 cm^{-1}) than in the forest (28.3 ± 13.5 Mg C ha^{-1} 30 cm^{-1}) or arable land (41.9 ± 16.9 Mg C ha^{-1} 30 cm^{-1}) ecosystems. The SOC stock ranged from 15.3 ± 1.7 in PF to 248.7 ± 168.6 Mg C ha^{-1} 30 cm^{-1} in MG. Among the forest ecosystems, WF had a significantly higher SOC stock than the others. Among the arable land ecosystems, AAL had a significantly higher SOC stock than the others. Among the thermokarst ecosystems, DG had a significantly lower SOC stock than the MG and WG.

The SCC stock were 7.9 ± 9.7 Mg C ha^{-1} 30 cm^{-1} in the forest, 12.3 ± 12.3 Mg C ha^{-1} 30 cm^{-1} in the arable land, 13.4 ± 11.4 Mg C ha^{-1} 30 cm^{-1} in the thermokarst ecosystems and ranged from 4.1 ± 3.1 in PG to 18.5 ± 20.2 Mg C ha^{-1} in PF. There was no significant difference between any

ecosystems and land uses. The TSC stock was significantly higher in the thermokarst ecosystem (150.5 ± 123.9 Mg C ha^{-1} organic horizon + 30 cm^{-1}) than in the forest (51.4 ± 20.9 Mg C ha^{-1} organic horizon + 30 cm^{-1}) or arable land (54.6 ± 23.1 Mg C ha^{-1} organic horizon + 30 cm^{-1}) ecosystems. The TSC stock ranged from 34.0 ± 13.1 in WAL to 266.9 ± 162.6 Mg C ha^{-1} organic horizon + 30 cm^{-1} in MG. Among the forest ecosystems, WF had a significantly higher TSC stock than the BF. Among the arable land ecosystems, AAL had a significantly higher TSC stock than the others. Among the thermokarst ecosystems, DG had a significantly lower TSC stock than the MG and WG.

Among the soil types, Histsols (219.4 ± 138.9 Mg C ha^{-1} organic horizon + 30 cm^{-1}) and Fluvisols (212.7 ± 162.2 Mg C ha^{-1} organic horizon + 30 cm^{-1}) had significantly higher TSC stocks than Stagnosols (71.5 ± 26.5 Mg C ha^{-1} organic horizon + 30 cm^{-1}), Cambisols (66.1 ± 39.9 Mg C ha^{-1} organic horizon + 30 cm^{-1}), Cryosols (50.9 ± 20.3 Mg C ha^{-1} organic horizon + 30 cm^{-1}), and Spodosols (40.6 ± 18.0 Mg C ha^{-1} organic horizon + 30 cm^{-1}).

The composition ratios of the C stock are shown in Fig. 4. Although the composition ratio of TSC stock significantly differed among the ecosystem, the SOC stock was the main component of the TSC stock (ranging from 47.4% in the PF to 96.4% in the PG). The percentage of LIC and SCC in the TSC ranged from 4.4 ± 4.5% in NAL to 37.8 ± 11.1% in PF, and from 3.6 ± 2.7% in PG to 32.6 ± 35.7% in PF.

Fig. 5 shows the SOC stocks in the 0–30 cm soil layers. Several studies have estimated the SOC stock in permafrost (Cryosol) and permafrost-affected soils in the boreal and arctic regions. Although SOC values in grasslands of the thermokarst ecosystem were within the ranges found in previous studies, the forest and arable land ecosystem values were at the lower-end of those found in previous studies.

3.2. Factors affecting SOC content

Table 1 shows Pearson's correlation coefficients for SOC content and soil physico-chemical properties. In the forest ecosystems, the SOC content was significantly, positively correlated with silt content, water content, EC, and exchangeable Ca^{2+} and Mg^{2+}, and negatively correlated with sand content, BD, and pH. In the arable land ecosystems, SOC content was significantly, positively correlated with silt content and exchangeable K^{+}, and negatively correlated with sand content, BD, and pH. In the thermokarst ecosystems, SOC content was significantly, positively correlated with SCC content, water content, EC, and exchangeable Na^{+}, Ca^{2+}, and Mg^{2+}, and negatively correlated with BD and exchangeable K^{+}. For all land uses, SOC content was significantly, positively correlated with sand content, water content, EC, and exchangeable Na^{+}, Ca^{2+}, and Mg^{2+}, and negatively correlated with BD and pH.

Fig. 6 shows the relationship between root C density and SOC content. The root C density

1 was positively correlated with the SOC content.

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3 *3.3. C recovery rate after abandonment of arable land*

4 Fig. 7 shows the annual average C recovery rate in AAL and NAL after the abandonment of

5 arable land. The SOC recovery rate in AAL was 1.49 ± 1.26 Mg C ha^{-1} 30 cm^{-1} yr^{-1} at five years

6 after abandonment, which decreased to 0.85 ± 0.79 at 20 years and 0.19 ± 0.28 Mg C ha^{-1} at 30

7 cm^{-1} yr^{-1} at 36 years after abandonment. The SOC recovery rate in NAL was relatively slower

8 than in AAL. The SCC recovery rate was slower than the SOC recovery rate and almost

9 constant regardless of the years after abandonment. Consequently, the TSC recovery rate was

10 higher in AAL than in NAL.

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4. Discussion

4.1. Factors affecting SOC

We found a significant, positive correlation between root C density and SOC content, regardless of the ecosystem (Fig. 6). Several studies have reported that root biomass plays an important role in soil C accumulation through fine root mortality in the forest and arable land ecosystems (Mazzilli et al., 2015). Mazzilli et al. (2015) analyzed changes in $\delta^{13}C$ natural abundance in OM and found that belowground biomass contributed from 60 to almost 80% of the total new C present in the OM. Moreover, Limin et al. (2015) estimated the C budget of managed grassland using a combination of eddy covariance and the biometric method and concluded that root litter might remain in the soil and is a significant contributor to the grassland soil C stock. Our results support those of these previous studies.

We also found a significant effect of soil texture on SOC accumulation in the forest and arable land ecosystems (Table 1). The SOC content is usually high in fine-textured soils and low in coarse-textured soils (Barre et al., 2017; Gonçalves et al., 2017), because of the association between clay particles and soil C that forms clay-humic complexes that play a fundamental role in C protection against microbial oxidation (Bronick and Lal, 2005). However, the SOC content was not as strongly correlated with the clay content ($P = 0.09$ for the forest and $P = 0.12$ for the arable land ecosystems) as it was with the silt content in both the forest and

arable land ecosystems ($P < 0.01$). This suggests that SOC accumulates in fine pores inside aggregates formed by the orientation of silt particles, rather than by chemically bonding with clay minerals (Barré et al., 2014; Blanco-Moure et al., 2016; Li and Shao, 2014).

The SOC content in the thermokarst ecosystems was not affected by soil texture but by water content (Table 1), and a strong, positive correlation between water content and SOC content was also observed in the forest ecosystems and all land use types (Table 1). Soil moisture affects OM decomposition by affecting oxygen diffusion into the soil and substrate availability for soil microorganisms (Tang et al., 2017; Xu et al., 2016). Consequently, a high SOC content is observed in wet rather than dry conditions in the boreal region (Henkner et al., 2016).

4.2. C stocks in the thermokarst ecosystems

Significantly higher SOC and TSC stocks were observed in the thermokarst ecosystems than in the forest or arable land ecosystems (Fig. 3), which agrees with previous studies conducted in this region (Desyatkin and Desyatkin, 2006; Matsuura et al., 1994). This result indicates C accumulation during thermoakrst formation, when surface soils in the thermokarst depression are buried by the LD horizon (Desyatkin and Desyatkin, 2006). After a long period, grassland vegetation on the bottom of the depression increases C stocks (Matsuura et al., 1994). In the thermokarst ecosystems, SOC, the main component of TSC (Fig. 4), was affected by soil water

content and root C density (Table 1; Fig. 6). Higher water content and the root C density explained the significantly higher SOC stock in the MG and WG than DG. Moreover, soil temperature has a large effect on SOM decomposition: SOM decomposition increase exponentially with increase in soil temperature (Limin et al., 2015; Shimizu et al., 2009). Takakai et al., 2008 showed soil temperature tended to be higher in DG and PG than WG. These results may indicate that high water content in MG and WG kept soil temperature low and suppressed SOM decomposition.

Several field studies have reported that thermokarst activity is significantly increasing and the permafrost underneath is thawing, a process caused by both the warming described above and shifting hydrological processes (Crate et al., 2017; Fedorov et al., 2014; Ulrich et al., 2017). For example, from 1980 to 2012, the area covered by thermokarst lakes at the Yukechi site in this region has increased four-fold (Crate et al., 2017). These results suggest that thermokarst formation accumulates OM, and further flooding increases the C stock. However, Desyatkin et al. (2014) reported, based on four years' field observations, that under future global climate change, thermokarst depressions in Central Yakutia have the potential for lake expansion, causing a significant increase in methane emission in the region. Moreover, C stocks in the larch trees were not considered in this study. The effect of recent thermokarst activity on regional C budget should be carefully considered including not only soil C stock change but also the other

C flows.

4.3. Effect of forest disturbance on C stocks

In this study, the LIC stock was significantly decreased by forest disturbance at an average rate of 51.7 ± 65.0% in the BF and 58.5 ± 62.4% in the WF.

The effects of forest fires on the LIC stock are highly variable, and mainly depend on the fire's intensity (Cui et al., 2014). Hatano et al. (2006) reported that 51% of LIC (8.6 Mg C ha^{-1}) has been lost due to forest fires in Central Yakutia. The value that we obtained in this study was similar, and comparable to moderate-intensity surface fire values as proposed by Conard et al. (2002).

The effect of water damage on boreal forest C stocks has been little-studied (Ohta et al., 2014). In this study, water damage decreased LIC stocks almost as much as a forest fire. According to Ohta et al. (2014), the number of living larch trees decreased by 15% from 1998 to 2011, and gross primary production was significantly reduced by waterlogging. These results indicate that a significant decline in LIC may decrease C input.

Forest fires did not change the SOC stock, but waterlogging significantly increased it (Fig. 3).

The effects of forest fire on the SOC are also mediated by the fire's intensity (Cui et al., 2014). Fernández et al. (1999) reported SOC losses greater than 50% in the upper 0–10 cm layer

caused by a high-intensity forest fire. In contrast, low-intensity fires can increase SOC in surface soils by 10 to 30% (Certini et al., 2011; Cui et al., 2014). Cui et al. (2014) reported that there was no significant difference in SOC stocks after low- and moderate-intensity fires in China. No significant change in the SOC stock in our study suggests that the loss of SOC by direct combustion in a fire and the C input from dry leaves and partially burnt plant materials is balanced after a moderate-intensity fire (Cui et al., 2014).

The SOC stocks in the forest ecosystems were strongly affected by the soil water content, as discussed in the previous section, because waterlogging significantly increased the soil water content, which significantly increased the SOC stock.

As a consequence, no significant change in the TSC stock was caused by any type of forest disturbance, however, forest disturbances altered the composition ratio of the C stock (Fig. 6). These results indicating that redistribution on C stock had occurred by land use change under the climate change.

4.4. Effects of forest cultivation and abandonment of arable land on C stocks

Conversion of the LF to the WAL did not change the SOC or SCC stocks (Fig. 3); however, 18.5 ± 7.7 Mg C ha^{-1} of the LIC stock that was originally stored in the organic horizon of the LF was diminished, which as a consequence, significantly decreased the TSC stock at an average

rate of 37.3 ± 47.2%. Converting forest to arable land results in OM mineralization (Don et al., 2011). In the midwestern United States, the majority of soils that have been converted from natural to agricultural systems have lost 30–50% of their original C stock (Lal, 2002). The TSC reduction rate observed in the present study was similar to that found in previous studies, but there was no significant difference in SOC stock between LF and WAL. Many studies have shown that the conversion of forest to cropland often leads to a decrease in SOC stock (Ajami et al., 2016; Assefa et al., 2017; Fujisaki et al., 2017). Assefa et al. (2017) reported that deforestation and agriculture have resulted in a 48.2% decrease in the SOC stock in northwest Ethiopia under a tropical climate. Fujisaki et al. (2017) evaluated the effects of deforestation on SOC stocks in the 0–30 cm soil layer in Amazonia under a humid tropical climate, and showed that the SOC stock had decreased by 17.8% compared to that in the original forest. Previous studies have found that the reduction rate is highly variable. Victoria et al. (2012) showed that the SOC stock reduction rate associated with forest conversion depends upon the climate and is more intense and rapid in tropical area than in humid temperate area. This may be attributed to the difference in the C turnover rate associated with land use changes, which is mainly affected by temperature and moisture (Chen et al., 2013). In this study, the extremely low annual air temperature (-9.7 ºC) and precipitation (235 mm) under an extracontinental climate might have prevented SOC mineralization caused by deforestation.

In contrast to deforestation, arable land abandonment leads to SOC accumulation (Kalinina et al., 2015; Kurganova et al., 2015). Kalinina et al. (2015) investigated post-agrogenic plant succession and C stocks in Russia, and found that during self-restoration, the vegetation and soil develop towards their natural condition. In this study, the abandonment of arable land significantly increased the SOC stock. As a consequence, the TSC stock in AAL had almost recovered to the same level as in LF (Fig. 3). In AAL, during self-restoration, the vegetation developed towards a steppe. The continuous presence of vegetation provided the SOM protection, and contributed to C accumulation (Soussana et al., 2004). Additionally, the root C density in the AAL tended to be higher than that in WAL (Fig. 6). It could be one of the causes for the larger SOC stock in AAL than WAL. However, in NAL, there was no significant C accumulation compared with that in WAL. In the case of boreal arable land restoration, the dynamics of vegetation recovery and C stocks are closely related (Ryzhova et al., 2014), and a study conducted on the southern taiga found that meadow succession after arable land restoration inputs more C than young forest succession (Ryzhova et al., 2014).

The time period after abandonment was closely related to the C accumulation rate. The highest rate of SOC_{rec} was observed in the earliest stage of the abandonment, before decreasing in the latter period (Fig. 7). This result supports those of studies conducted in Russia and Kazakhstan by Kurganova et al. (2014) and Kurganova et al. (2015). Kurganova et al. (2014)

reported that the average SOC accumulation rate in the 0–20 cm soil layer was 0.96 ± 0.08 Mg C ha^{-1} 20 cm^{-1} yr^{-1} for the first 20 years after abandonment and 0.19 ± 0.10 Mg C ha^{-1} 20 cm^{-1} yr^{-1} during the next 30 years. Belelli Marchesini et al. (2007) reported that the average SOC accumulation rate in the 0–5 cm soil layer of abandoned cropland was 0.66 Mg C ha^{-1} 5 cm^{-1} yr^{-1}, and there was a tendency towards SOC saturation on abandoned land, as sequestration rates were much higher on recently abandoned land (1–10 years old, 1.04 Mg C ha^{-1} 5 cm^{-1} yr^{-1}) than on earlier-abandoned crop fields (11–20 years old, 0.26 Mg C ha^{-1} 5 cm^{-1} yr^{-1}). Our calculated SOC recovery rates were comparable, but at an early stage of abandonment, the highest rate of SOC accumulation was observed in this study. Our estimation was based on the upper 30 cm of the soil profile, whereas Belelli Marchesini et al. (2007) and Kurganova et al. (2014) based their estimations on the upper 5 and 20 cm, respectively. This suggests that the effects of arable land abandonment on SOC accumulation occur not only in the topsoil but also in soils as deep as 30 cm (Liu et al., 2017; Sheng et al., 2015).

Net ecosystem production (NEP) is estimated as the C budget, which almost equals the change in the SOC stock in natural ecosystems (Bernacchi et al., 2005; Randerson et al., 2002). Kurganova et al. (2015) estimated the NEP during the first 20 years after cropland abandonment in Asian Russia, and summarized NEP values that had been reported in Russia and Kazakhstan (Belelli Marchesini et al., 2007; Kurganova et al., 2007; Perez-Quezada et al., 2010). The NEP

values ranged from 1.47 to 2.96 Mg C ha^{-1} yr^{-1}, and the average value was 2.23 ± 0.42 Mg C ha^{-1} yr^{-1}. These values are comparable to the SOC accumulation rate in this study, but slightly higher. These results indicating that land use change induced by human activity clearly changed the C budget.

4.5 SCC stock

Although SOC stock was a main component of the TSC stock and there was no significant difference between any ecosystems and land uses, SCC accounted for 13.5 ± 15.6% in the forest, 19.5 ± 15.6% in the arable land, and 12.8 ± 13.1% in the thermokarst ecosystem of TSC (Fig. 4). Many national and regional databases of C stock consider SOC, but not SCC (Rawlins et al., 2011). However, Batjes, (1996) estimated that one-third of the global carbon stock in the upper 1 m of soil was the SCC. And Lal, 2004 estimated 38% of the soil C stock is existing as a SCC. It is said that SCC has a long turnover time compared with SOC and it is the dominant form of C in arid and semi-arid climates (He et al., 2016). Therefore, to estimate the soil C pool in terrestrial ecosystems, both SOC and SCC should be considered.

5. Conclusion

LIC, SOC, and TSC stocks of the three ecosystems were significantly different. Significantly higher SOC and TSC stocks were found in the thermokarst ecosystem, suggesting that thermokarst formation accumulates OM. Forest disturbance significantly changed the C balance in the forest ecosystem. In the arable land ecosystem, after the abandonment of arable land, SOC and TSC was significantly restored. Root biomass plays an important role in soil C accumulation through fine root mortality. In the forest and arable land ecosystems, soil texture strongly affected SOC content, whereas water content was the main factor that affected SOC accumulation in the thermokarst ecosystem. This study revealed that redistribution of the C stock has been occurred under the climate change and human activity.

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List of figures

Fig. 1. Location of the study sites (adapted from Schuur et al., 2008).

Fig. 2. Thermokarst stages in ice-rich permafrost in the boreal zone of Central Yakutia. adapted from Crate et al., 2017).

Fig. 3. Different uppercase letters indicate significant differences between ecosystems, and different lowercase letters indicate significant differences between land use types in the same ecosystem. LIC: Litter carbon, SOC: Soil organic carbon, SCC: soil carbonate carbon, LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo.

Fig. 4. Composition ratio of carbon stocks in the 0–30 and 0–100 cm soil layers. LIC: Litter carbon, SOC: Soil organic carbon, SCC: Soil carbonate carbon, LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo

Fig. 5. Comparison of soil organic carbon (SOC) stocks in permafrost and permafrost-affected soils. †: Cryosol, ‡: Permafrost soils. SOC: Soil organic carbon, LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry

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Fig. 6. Relationships between root carbon density and soil organic carbon content. SOC: Soil organic carbon, LF: Larch forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: wet grassland, PG: Pingo.

Fig. 7. Annual average carbon recovery rate on abandoned arable land and new-growth arable land after abandonment. C_{rec}: Annual average rate of soil organic carbon stock recovery after the abandonment of working arable land. C_{rec} were calculated based on Kurganova et al. (2014). AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees.

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Pearson's correlation coefficients for soil organic carbon and soil physico-chemical properties.

SCC: Soil carbonate carbon, BD: Bulk density

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Table A-1

Comparison of the LIC, SOC, SCC, and TSC stock between ecosystems and land uses.

Different uppercase letters indicate significant differences between ecosystems, and different lowercase letters indicate significant differences between land use types in the same ecosystem. LIC: Litter carbon, SOC: Soil organic carbon, SCC: Soil carbonate carbon, TSC: Total soil carbon, LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo.

Table A-2
Comparison of the LIC, SOC, SCC, and TSC stock between soil types.

Different lowercase letters indicate significant differences between soil types. LIC: Litter carbon, SOC: Soil organic carbon, SCC: Soil carbonate carbon, TSC: Total soil carbon.

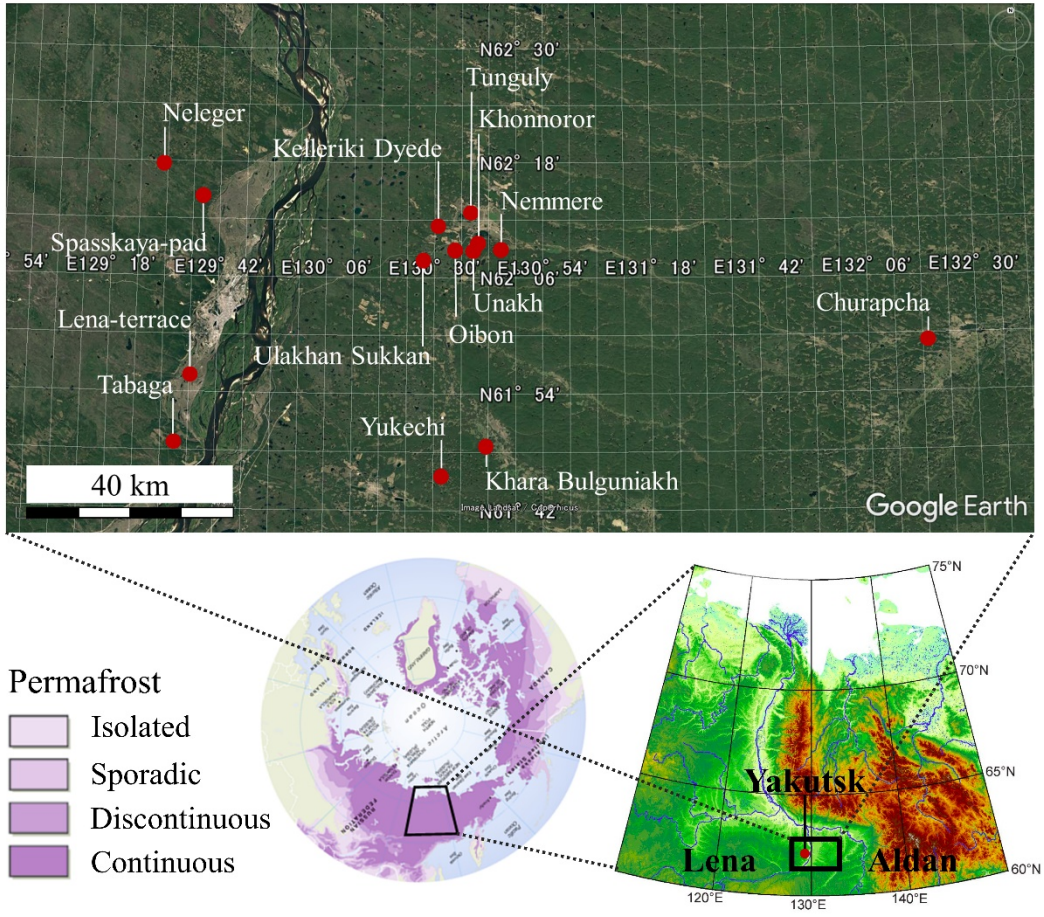


Fig. 1. Location of the study sites (adapted from Schuur et al., 2008).

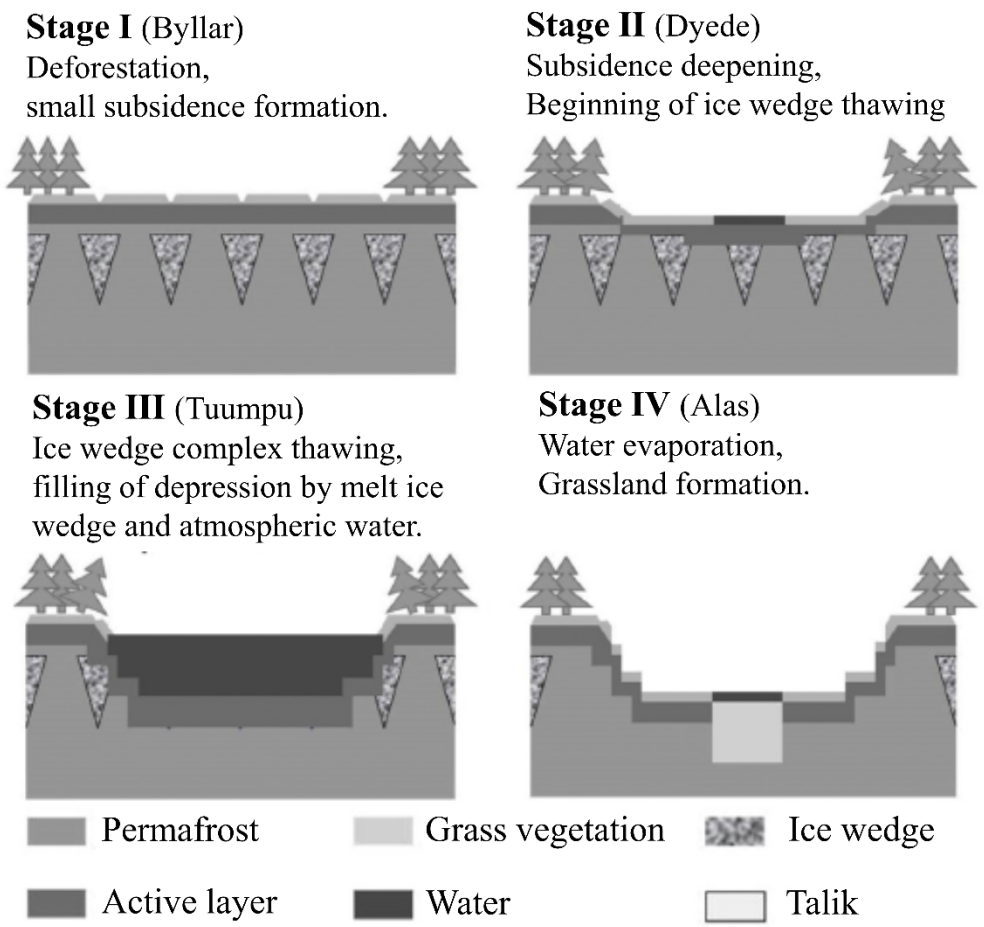
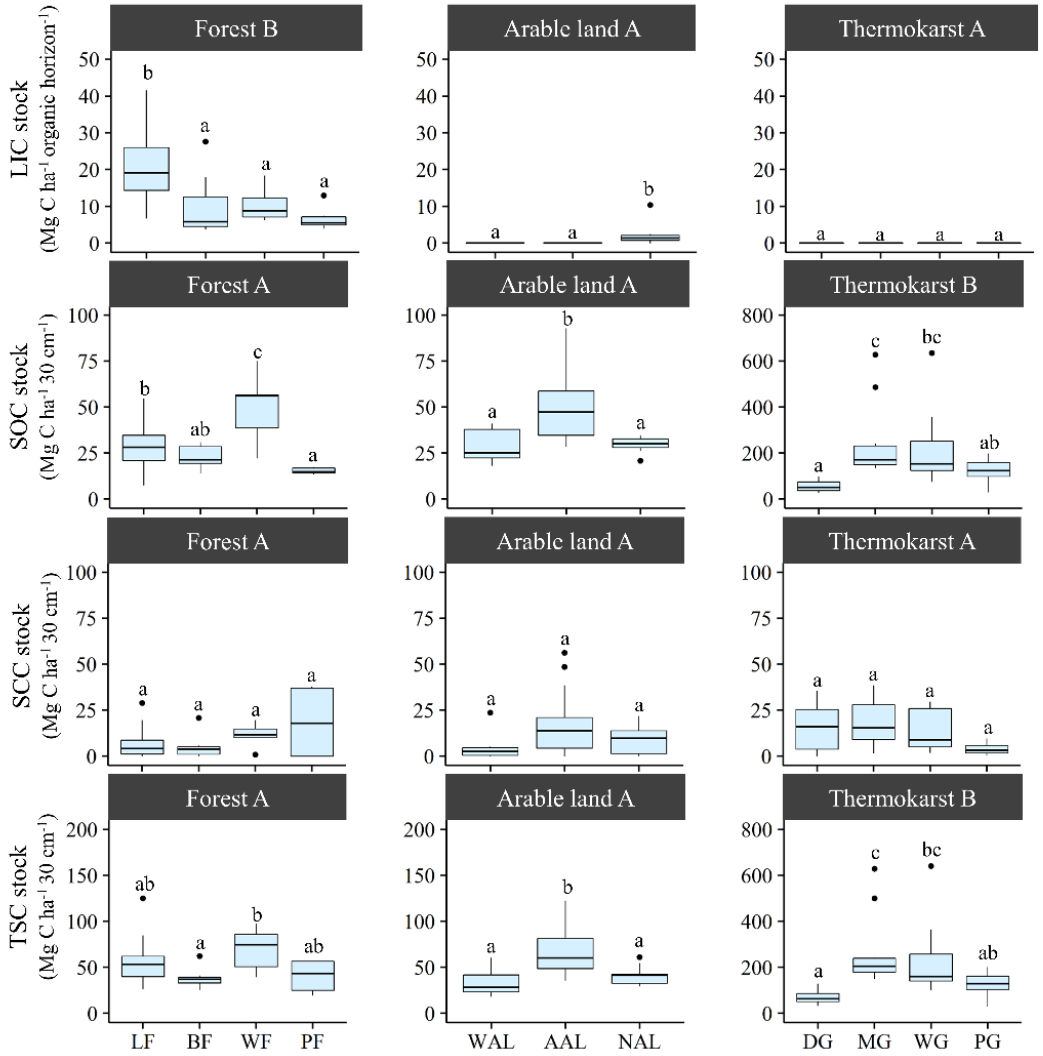


Fig. 2. Thermokarst stages in ice-rich permafrost in the boreal zone of Central Yakutia. adapted from Crate et al., 2017).



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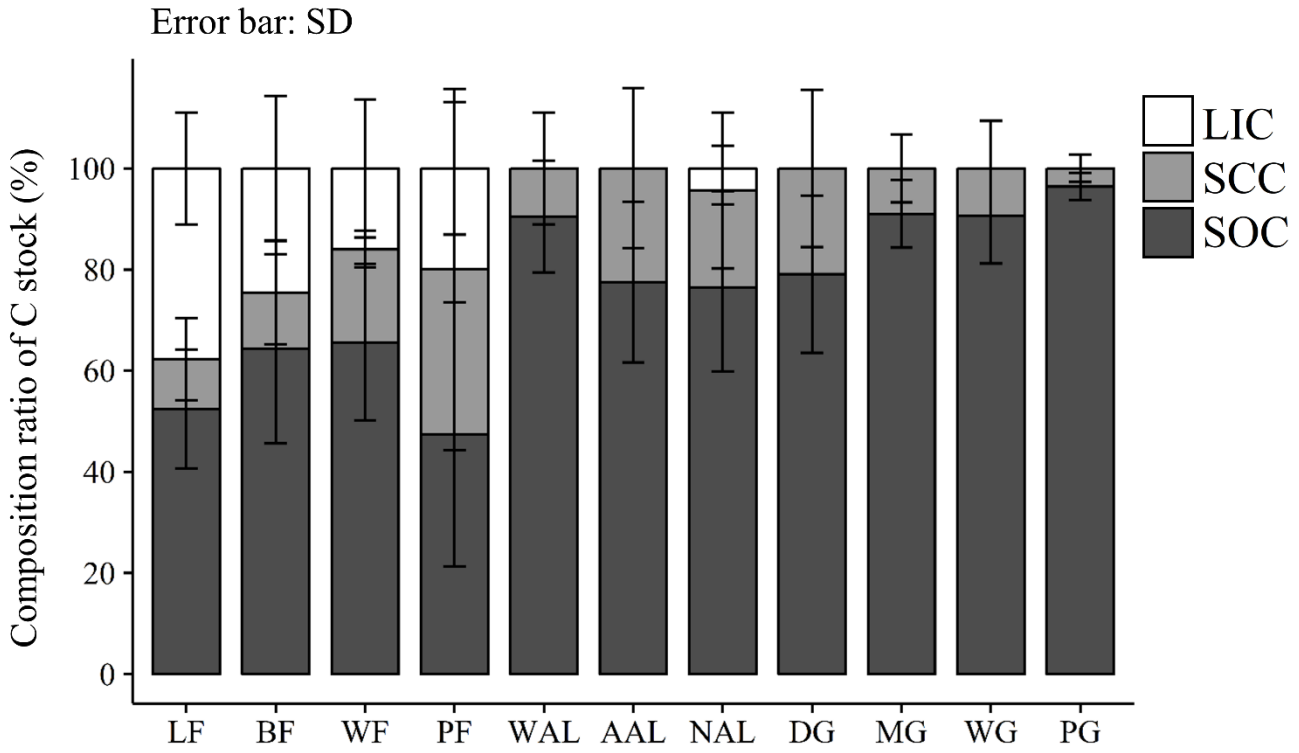

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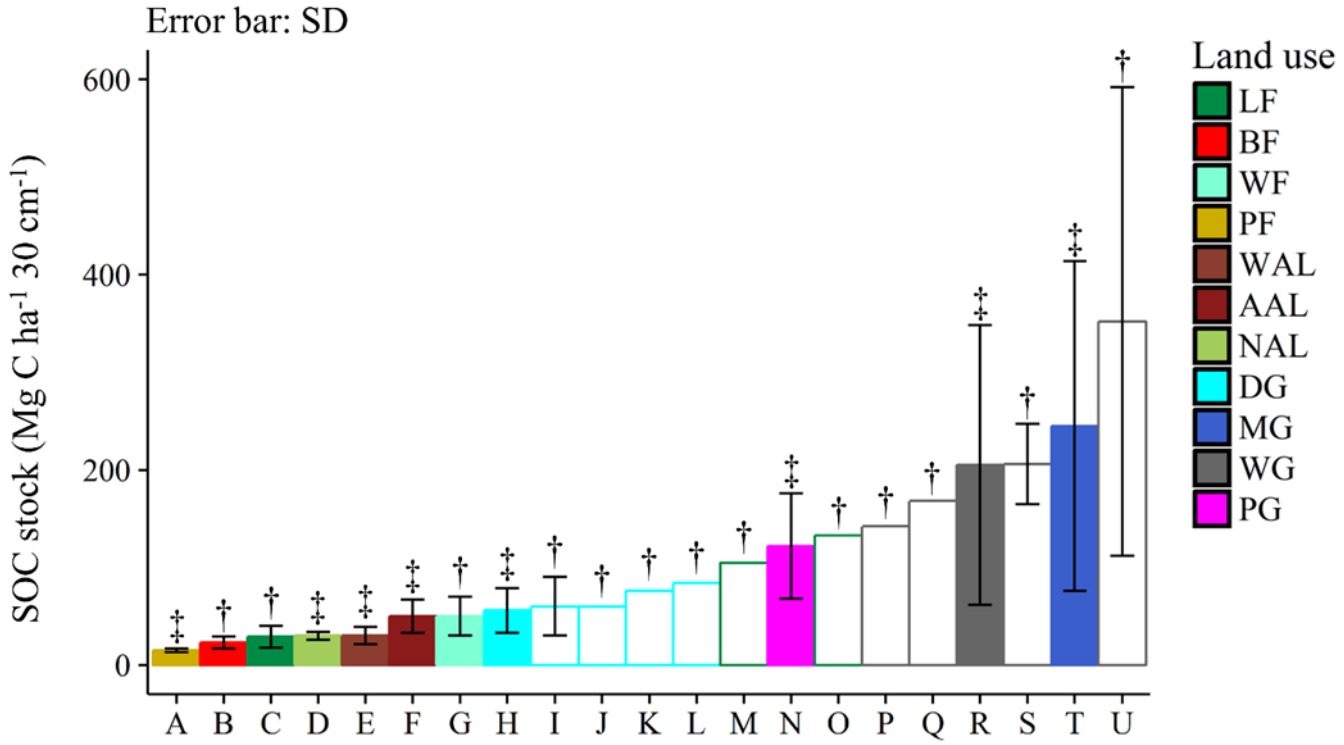

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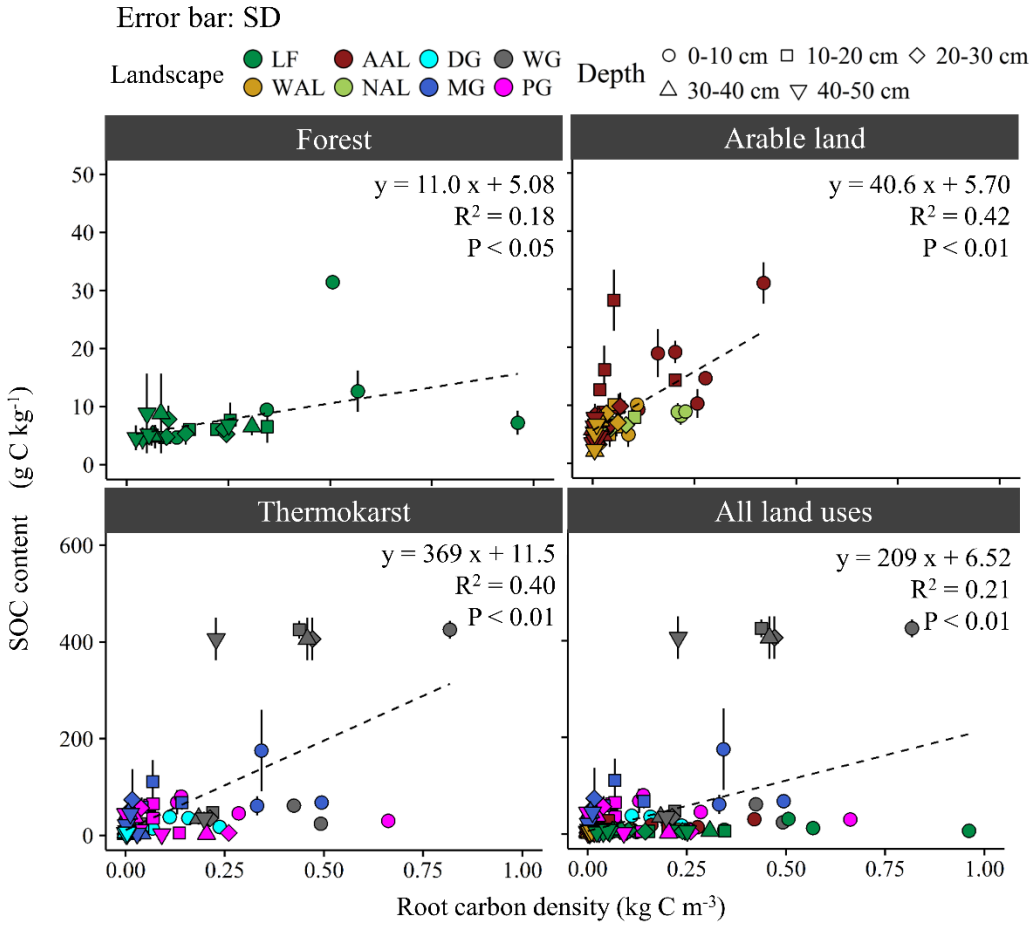
Error bar: SD
Landscape
LF
AAL
DG
WG
WAL
NAL
MG
PG
Depth
0-10 cm
10-20 cm
20-30 cm
30-40 cm
40-50 cm
Forest
y = 11.0 x + 5.08
R² = 0.18
P < 0.05
Arable land
y = 40.6 x + 5.70
R² = 0.42
P < 0.01
Thermokarst
y = 369 x + 11.5
R² = 0.40
P < 0.01
All land uses
y = 209 x + 6.52
R² = 0.21
P < 0.01
SOC content (g C kg⁻¹)
Root carbon density (kg C m⁻³)
0
10
20
30
40
50
200
400
600
0.00
0.25
0.50
0.75
1.00

Fig. 6. Relationships between root carbon density and soil organic carbon content. SOC: Soil organic carbon, LF: Larch forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: wet grassland, PG: Pingo.

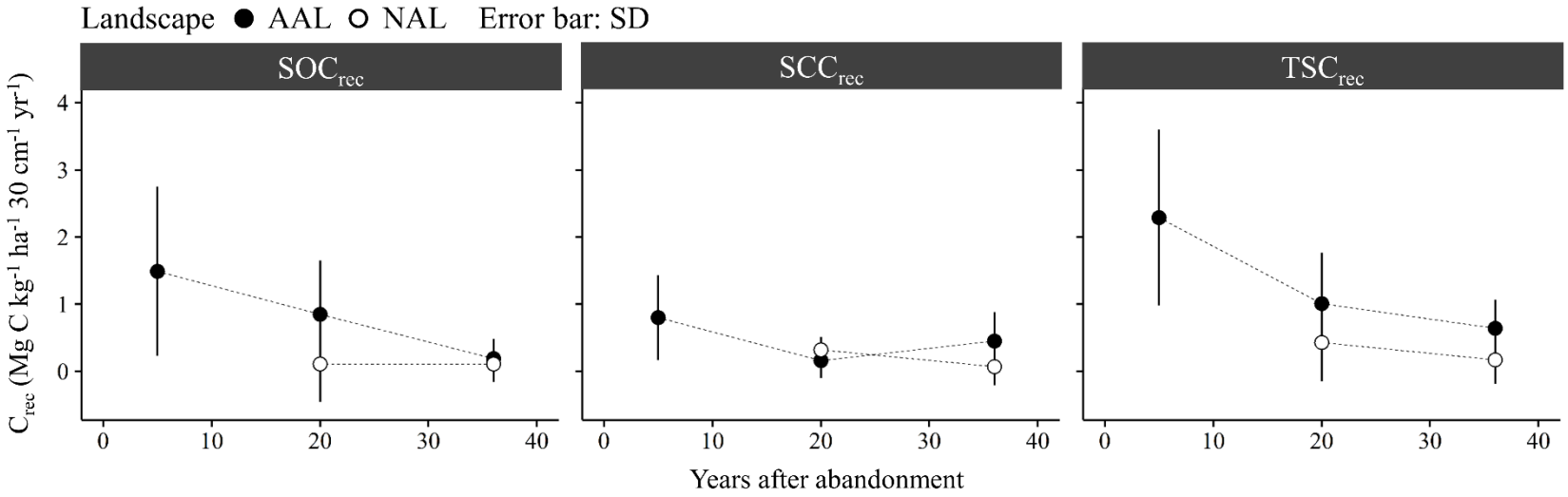

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Table 1
Pearson's correlation coefficients for soil organic carbon and soil physico-chemical properties.

	Forest			Arable land			Thermokarst			All land uses		
	n	r	P-value	n	r	P-value	n	r	P-value	n	r	P-value
SCC content (g C kg^{-1})	163	-0.05	0.52	242	-0.02	0.80	177	0.20	P < 0.01	600	0.03	0.47
Sand content (%)	83	-0.33	P < 0.01	110	-0.39	P < 0.01	52	0.25	0.09	245	0.15	P < 0.05
Silt content (%)	83	0.41	P < 0.01	110	0.43	P < 0.01	52	-0.24	0.10	245	-0.12	0.06
Clay content (%)	83	0.19	0.09	110	0.15	0.12	52	-0.15	0.30	245	-0.12	0.07
Water content (%, kg kg^{-1})	202	0.57	P < 0.01	169	0.15	0.06	177	0.80	P < 0.01	560	0.65	P < 0.01
BD (Mg m^{-3})	218	-0.82	P < 0.01	242	-0.84	P < 0.01	177	-0.69	P < 0.01	637	-0.77	P < 0.01
pH	143	-0.61	P < 0.01	240	-0.52	P < 0.01	177	-0.09	0.27	572	-0.34	P < 0.01
EC (m S m^{-1})	112	0.25	P < 0.05	187	-0.03	0.72	177	0.15	P < 0.05	488	0.16	P < 0.01
Exchangeable Na^{+} ($cmol_c$ kg^{-1})	20	-0.08	0.73	90	0.01	0.92	46	0.57	P < 0.01	156	0.34	P < 0.01
Exchangeable K^{+} ($cmol_c$ kg^{-1})	20	0.26	0.28	90	0.37	P < 0.01	46	-0.31	P < 0.05	156	-0.08	0.31
Exchangeable Ca^{2+} ($cmol_c$ kg^{-1})	20	0.47	P < 0.01	90	0.12	0.27	46	0.66	P < 0.01	156	0.19	P < 0.05
Exchangeable Mg^{2+} ($cmol_c$ kg^{-1})	20	0.47	P < 0.01	90	0.07	0.51	46	0.89	P < 0.01	156	0.88	P < 0.01

SCC: Soil carbonate carbon, BD: Bulk density

Table A-1
Comparison of the LIC, SOC, SCC, and TSC stock between ecosystems and land uses.

LIC stock (Mg C ha^{-1})					
Ecosystem	Land use	Organic horizon			
		n	Mean	SD	
Forest	LF	31	20.5	9.4	b
	BF	9	9.9	8.1	a
	WF	5	8.5	6.7	a
	PF	6	6.7	3.3	a
Arableland	WAL	11	0	0	a
	AAL	38	0	0	a
	NAL	13	1.9	2.7	b
Thermokarst	DG	25	0	0	a
	MG	10	0	0	a
	WG	16	0	0	a
	PG	12	0	0	a
Forest		51	16.1	10	B
Arableland		62	0.4	1.4	A
Thermokarst		63	0	0	A

SOC stock (Mg C ha^{-1})					
Ecosystem	Land use	0–30 cm soil			
		n	Mean	SD	
Forest	LF	33	28.8	11.2	b
	BF	9	23	5.9	ab
	WF	5	49.8	20.1	c
	PF	6	15.3	1.7	a
Arableland	WAL	11	29.8	8.9	a
	AAL	38	49.5	17	b
	NAL	13	29.8	3.9	a
Thermokarst	DG	25	56.1	22.5	a
	MG	10	248.7	168.6	c
	WG	16	205.3	143.9	bc
	PG	12	121.9	54.2	ab
Forest		53	28.3	13.5	A
Arableland		62	41.9	16.9	A
Thermokarst		63	137.1	125.5	B

SCC stock (Mg C ha^{-1})					
Ecosystem	Land use	0–30 cm soil			
		n	Mean	SD	
Forest	LF	33	6.2	6.7	a
	BF	9	5	6.3	a
	WF	5	11.4	6.9	a
	PF	6	18.5	20.2	a
Arableland	WAL	11	4.2	6.7	a
	AAL	38	15.8	13.5	a
	NAL	13	8.7	7.8	a
Thermokarst	DG	25	15.5	11.7	a
	MG	10	18.2	12.9	a
	WG	16	14	10.8	a
	PG	12	4.1	3.1	a
Forest		53	7.9	9.7	A
Arableland		62	12.3	12.3	A
Thermokarst		63	13.4	11.4	A

TSC stock (Mg C ha^{-1})					
Land use	Land use	Organic horizon + 0–30 cm soil			
		n	Mean	SD	
Forest	LF	31	54.2	20.6	ab
	BF	9	37.8	10.6	a
	WF	5	69.7	24.2	b
	PF	6	40.6	18	ab
Arableland	WAL	11	34	13.1	a
	AAL	38	65.4	22.1	b
	NAL	13	40.4	9.3	a
Thermokarst	DG	25	71.5	26.5	a
	MG	10	266.9	162.6	c
	WG	16	219.4	138.9	bc
	PG	12	125.9	54.5	ab
Forest		51	51.4	20.9	A
Arableland		62	54.6	23.1	A
Thermokarst		63	150.5	123.9	B

Different uppercase letters indicate significant differences between ecosystems, and different lowercase letters indicate significant differences between land use types in the same ecosystem. LIC: Litter carbon, SOC: Soil organic carbon, SCC: Soil carbonate carbon, TSC: Total soil carbon, LF: Larch forest, BF: Burned larch forest, WF: Water damaged larch forest, PF: Pine forest, WAL: Working arable land, AAL: Abandoned arable land, NAL: Abandoned arable land invaded by new-growing trees, DG: Dry grassland, MG: Moderately wet grassland, WG: Wet grassland, PG: Pingo.

Table A-2
Comparison of the LIC, SOC, SCC, and TSC stock between soil types.

LIC stock				
Soil type	Organic horizon			
	n	Mean	SD	
Cryosols	40	18.1	10.1	c
Spodosols	6	6.7	3.3	b
Cambisols	74	0.3	1.3	a
Stagnosols	25	0	0	a
Fluvisols	14	3	5.6	ab
Histosols	16	0	0	a

SOC stock				
Soil type	0–30 cm soil			
	n	Mean	SD	
Cryosols	42	27.6	10.5	a
Spodosols	6	15.3	1.7	a
Cambisols	74	54.9	39.5	a
Stagnosols	25	56.1	22.5	a
Fluvisols	15	182.4	166.8	b
Histosols	16	205.3	143.9	b

SCC stock				
Soil type	0–30 cm soil			
	n	Mean	SD	
Cryosols	42	5.9	6.5	a
Spodosols	6	18.5	20.2	ab
Cambisols	74	11	11.7	ab
Stagnosols	25	15.5	11.7	b
Fluvisols	15	15.9	11.5	b
Histosols	16	14	10.8	ab

TSC stock				
Soil type	Organic horizon + 0–30 cm soil			
	n	Mean	SD	
Cryosols	40	50.9	20.3	a
Spodosols	6	40.6	18.0	a
Cambisols	74	66.1	39.9	a
Stagnosols	25	71.5	26.5	a
Fluvisols	14	212.7	162.2	b
Histosols	16	219.4	138.9	b

Different lowercase letters indicate significant differences between soil types. LIC: Litter carbon, SOC: Soil organic carbon, SCC: Soil carbonate carbon, TSC: Total soil carbon.